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The Impact of Additive Manufacturing on the Development of Electrical Machines for MEA Applications: A Feasibility Study

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Abstract This paper discusses the potential of Additive Manufacturing (AM) as an innovative means of manufacturing electrical machines, with particular focus on the benefits for the MEA. It is argued that the unrivalled design freedom offered by AM may revolutionise the way rotating electrical machines are designed and manufactured. Until now the design of standard electrical motors has not gone much beyond the two-dimensions, mainly due to constraints imposed by the manufacturing processes employed. The possibility offered by AM to extend the design to the three-dimensional space introduces new opportunities towards the fabrication of compact, highly performing electrical machines, whose impact would be highly beneficial especially for MEA-related applications. The challenges entailed, as well as the factors that might lead to the successful introduction of AM to the MEA world are investigated based on the existing literature.

Introduction

Unlike conventional methods that are either formative or subtractive, Rapid Prototyping (RP) builds up components layer by layer. The success of the RP technologies such as Selective Laser Sintering (SLS) derives from the possibility of creating parts with almost any shape at no added costs. However, in order for a part to be functional (i.e., with good mechanical properties), high density is desired. In this respect, Additive Manufacturing (AM) technologies such as Selective Laser Melting (SLM, shown in Fig. 1) have proven more valuable than RP/SLS in that they can achieve densities comparable to those obtained through classical subtractive and formative processes. Thus, AM offers the potential for moving from RP to rapid manufacturing. For this reason, SLM is emerging across a broad range of sectors, including automotive, medical and aerospace, for the creation of functional parts. One of the most prominent aerospace names regularly associated with AM is GE Aviation, which is leading the way with its plans to produce a fuel nozzle using SLM [1]. And it is again GE who promoted an online challenge for the design of a Titanium alloy engine bracket to be fabricated using AM [2].

Despite the employment of SLM for a vast range of metallic materials, including several Steels, and Titanium, Cobalt and Aluminum alloys [3-7], its application to soft ferromagnetic materials seems limited to one contribution [8], where the beneficial effect of SLM on the soft magnetic properties, namely saturation magnetization and coercivity, was shown for Iron-Nickel alloy. This indicates a gap in the literature, as it seems that the successful processing of magnetic core materials through AM has the potential to open the path to a new generation of high torque density electric motors, with a consequent direct impact on the development of MEA technologies.

The selection of candidate machine parts for fabrication using SLM should be performed taking into account 1) the availability and manufacturability of the materials they are composed of and 2) their potential for performance improvement through geometry design optimisation. These two issues are discussed

in the following section, in order to provide guidelines towards the successful introduction of electrical machines to AM/SLM. Next, an approach to fully exploit the characteristics of SLM in terms of design and processing is suggested. Finally, the benefits that the employment of AM could produce for the MEA are considered, using specific applicative examples.

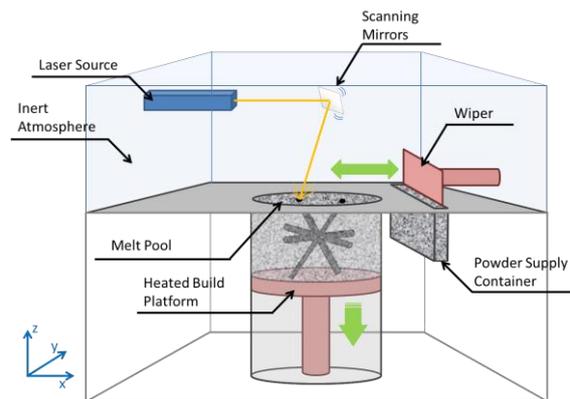


Fig. 1: Schematic of SLM main components and operating principle. The process starts with the wiper distributing a layer of powder from the supply chamber onto the build platform. A high-power laser beam is then applied selectively on the powder surface, according to the .stl file of the part. The energy fully melts the powders together before the build platform descends by one layer thickness along the z-axis. The process is repeated until completion of the final part.

Eligibility Criteria for Processing using SLM

Given the rather limited number of metallic elements that have been successfully processed by SLM to date, it seems reasonable to prioritize those alloys that are not too far from those whose processing has been shown to be feasible (e.g., Iron alloys). The advantage of this approach is twofold: first, it would make the availability of ready-to-use materials (i.e., atomized powders) from suppliers easier. Second, it would make it easier to determine the SLM-processing parameters. It should be kept in mind that,

although SLM technology currently allows for the processing of single materials only, multi-material applications may be envisaged. For such applications (e.g., rotors including a squirrel cage) post-processing steps for bringing the different parts together is required. The present paper discusses the optimisation through AM of single material applications only.

As regards the potential for improvement through AM, priority should be given to machine parts whose performance is mainly influenced by geometrical variables. In this respect, rotor shape optimisation represents a good example where the capability of AM to create unconstrained 3D shapes could be fully exploited for significant performance enhancement at no added cost.

Machine Topologies and Materials Affected

Based on the aforementioned criteria, the rotor of the Synchronous Reluctance Machine (SyRM) appears to be a good candidate for processing using SLM. The rotor of this machine is characterised by a very simple structure, composed entirely of soft magnetic material. Neither conducting material (e.g., the copper bars used in Squirrel Cage Induction Machines) nor permanent magnets are involved. Therefore, the performance of the SyRM mainly relies on rotor core geometry and its permeability. As the SyRM operates at synchronous speed, the rotor flux variation is minimal and its fabrication as a solid structure can be envisaged. This last point is paramount for a successful application of SLM, due to the well-known thermal gradient-induced deflections that would affect SLM-processed 2D structures [9].

With respect to the choice of materials, Cobalt-Iron (Co-Fe) alloys are considered a very attractive option for aerospace applications given their high saturation flux density and high resistance to harsh environments. Attempts to process Co-Fe using SLM have not been found in the literature, but a Cobalt-based alloy with structural functions, Co-Cr, is being extensively processed using SLM in the dental implant sector [6]. As regards to Fe-Si alloys, they represent excellent candidates for processing using SLM, since several other steel varieties have been successfully processed to date [3, 4]. In addition, SLM might foster the employment of 6.5%Si steels, which are known for their good magnetic properties such as high permeability, low hysteresis loss, high electrical resistivity, and low magnetostriction [10]. The commercial application of these alloys has been limited due to their poor ductility, which makes their processing difficult. Owing to the powder-based, layer manufacturing approach of SLM, the employment of 6.5%Si steels for machine cores can now be envisaged.

Design and Processing of Electrical Machines using SLM

Design Procedure: It is common that electrical machines created using classical manufacturing processes (e.g., laminate punching or alloy powder pressing) must be very carefully designed to facilitate the fabrication process; the material used for the

parts, the desired shape and features of the part and even the material properties of the processing machine must all be taken into account. Therefore, the typical design approach is to start from template geometries (e.g., a C-shaped flux barrier in a SyRM) and modify the associated size, depending on the application at hand and the required performance. The resulting component is thus far from optimal. Given the capability of AM of creating complex structures without the limits of conventional manufacturing techniques, a different approach to the design should be adopted, which is not limited to the optimisation of predefined sizes. In this respect, Topology Optimisation (TO) stands out as an appropriate tool for the creation of 3D designs that are as close as possible to unconstrained optimality and thus fully exploit the capabilities of AM. Deterministic and stochastic optimisation algorithms have been developed for the topological design of stator and rotor teeth in both two- and three-dimensions [11-14], and the three-dimensional geometry optimisation of a full Switched Reluctance Machine rotor carried out [15]. However, all of the mentioned attempts do not go beyond the proof-of-concept stage, and thus exclude any manufacturing-related issues and/or considerations. The issue of TO implementation for the design of real life objects to be fabricated using AM has been discussed for structural engineering problems in [16], but the guidelines provided are potentially applicable to electromagnetic devices as well.

Material Processing: The main issue encountered when introducing new materials to SLM is, besides the previously mentioned residual thermal gradient-induced deformations, the low density values of the processed part. In this respect, it is known [4] that a few key parameters play a paramount role in determining the density of the SLM-processed materials. These include:

- *Laser Power Density;*
- *Laser Exposure Time:* time of laser application on one single point;
- *Point distance:* distance between two consecutive points within the scanning area;
- *Hatch spacing:* distance between two parallel scanning tracks;
- *Laser Scanning Pattern.*

The above-mentioned parameters are material-dependent and should therefore be determined experimentally for each new alloy introduced to SLM. In the case of soft magnetic materials, control of the degree of orientation of the crystalline grains of the processed structure are especially of concern, as they determine whether the magnetic properties are the same in all directions (magnetic isotropy) or not (magnetic anisotropy). In this respect, a recent work

[17] suggests that the laser power can strongly influence the orientation of the crystalline grains in 316 L Stainless Steel. In particular, a highly-textured microstructure was claimed when a 1000W is employed for processing. As regards to soft magnetic alloys for electrical machines, the possibility of processing powders into grain-oriented structures at no added costs might open new opportunities in the development of electrical machines, where magnetic anisotropy can be taken advantage of [18].

Benefits of AM for the MEA

The Permanent Magnet Machine (PMM) is the most popular topology for aerospace applications [19, 20], mainly due to the high torque density, low losses and the possibility to make it fault tolerant [21]. As regards to the SyRM, this has been overlooked in the aerospace field because of its inferior torque density characteristics, the inter-dependency of its phase windings, which makes it inherently non fault-tolerant, and its relatively high torque ripple.

Up to the present SyRM flux barriers have been limited to being either C-, U- or I-shaped. In this respect, TO and AM are powerful tools for the introduction of innovative flux barrier designs, characterized by unconventional shapes in 3D. This, together with the possibility of extending the concept of continuous skewing and controlling the orientation of the crystalline grains through SLM-parameter tuning (as well as the introduction of concentrated windings [22] for fault-tolerance) might open the path to the employment of this low-cost and rugged machine to the aerospace sector. In particular, producing 3D, grain-oriented structures at no added cost – may lead to the implementation of novel solutions in MEA applications where axial, transverse and radial (3D) flux machines would be preferable due to the strict constraints in terms of volume availability, such as direct drive wheel actuation for green taxiing [23].

Summary and Conclusions

The present paper has discussed the possibility of fabricating electrical machinery using AM and the implications that this might have on the development of MEA-enabling technologies. It has been argued that laser-based AM, namely SLM, is a mature technology whose properties seem well-suited for tackling some of the issues related to electric machine design and manufacturing. Specifically, the employment of AM/SLM, alongside advanced design tools like TO, may enable the creation of innovative three-dimensional designs for magnetic core structures that are free from the constraints of classical manufacturing. The rotor of the SyRM appears particularly eligible for such improvements, since the performance of this machine mainly relies

on rotor core geometry and permeability. Improvements for this machine might include the conception of continuously skewed rotors and unconventional saliencies/flux barrier designs. As regards to materials, the introduction of both Fe-Si and Co-Fe alloys to SLM seems feasible, and experience with similar materials should help to identify suitable processing parameters. Furthermore, it has been shown that opportunities exist for the control of the magnetic properties of core materials through SLM-parameter fine-tuning.

In conclusion, it is suggested that the integration of SLM and TO-based design strategies has the potential to bring about benefits for the conception and manufacturing of electrical machinery, and ultimately for the MEA.

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